Numerical Methods in Biomechanics

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Content - schedule

W01: Organization, introduction and examples
W02: External lecturers
W03: Partial Differential Equations
W04: Solid mechanics in numerical biomechanics
W05: Fluid mechanics in numerical biomechanics
W06: The Finite Element Method (FEM), and its extensions
W07: Midterm evaluation
W08: Midterm project presentations
W09: Multiphysics, coupling, Comsol
W10: Multiphysics example 1
W11: Multiphysics example 2
W12: Multiphysics example 3
W13: Final project presentation

Numerical Methods in Biomechanics

A Patient-Specific Numerical Musculoskeletal Knee Model: Application to Patellar Resurfacing In Total Knee Arthroplasty

Adeliya Latypova

OUTLINE

1. Clinical problem

2. Limitations of the current state

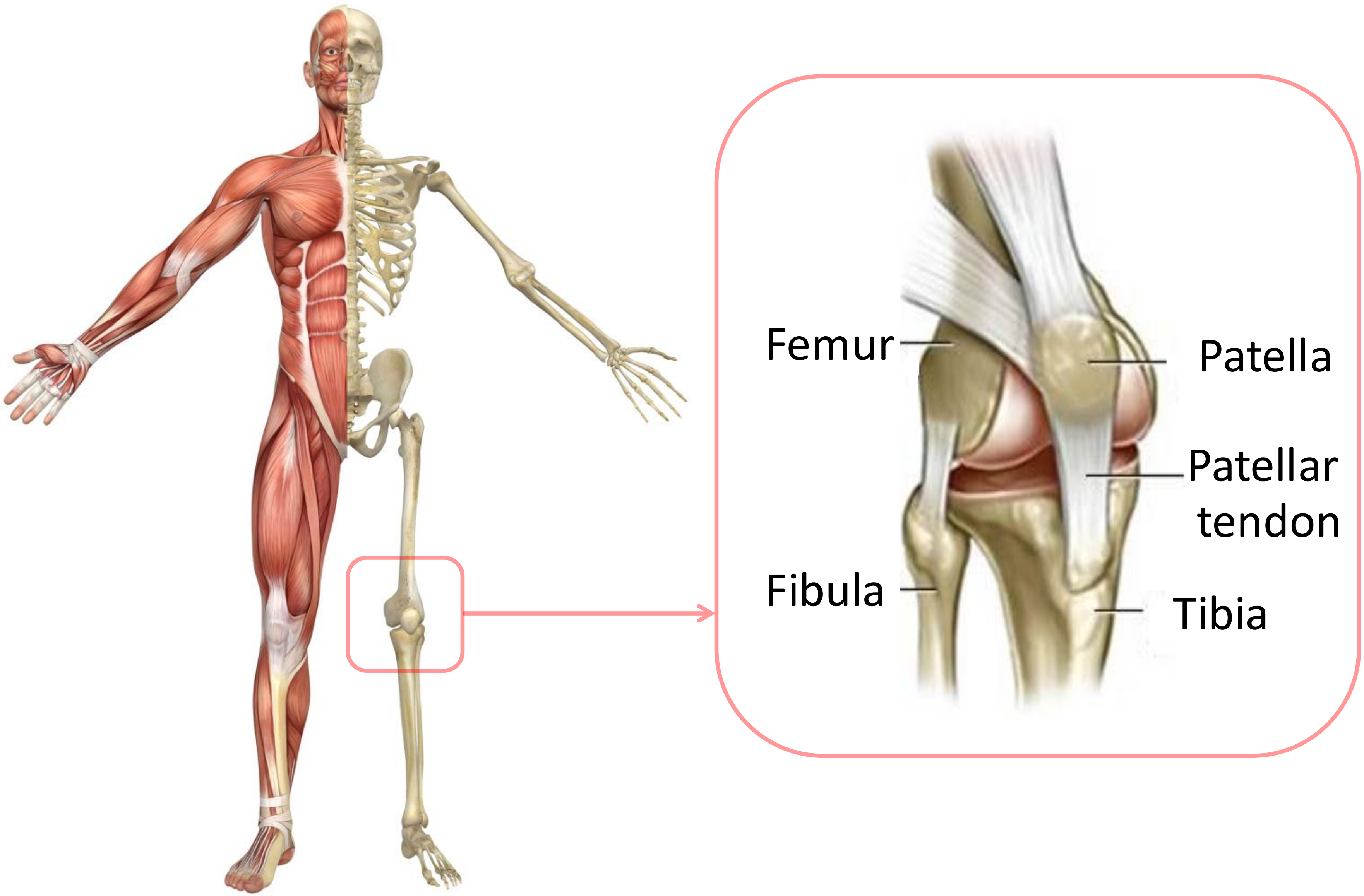
3. Objectives

4. Model development

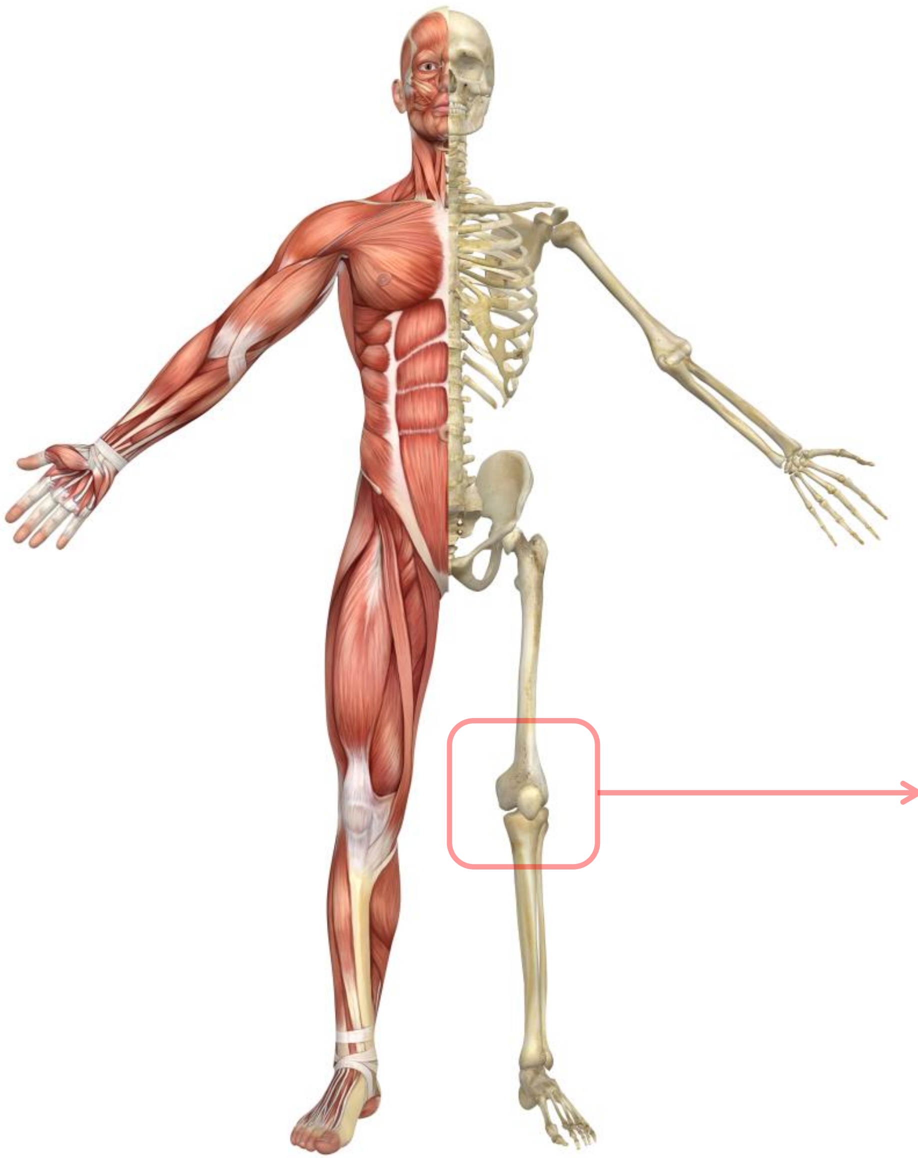
5. Application

6. Conclusions

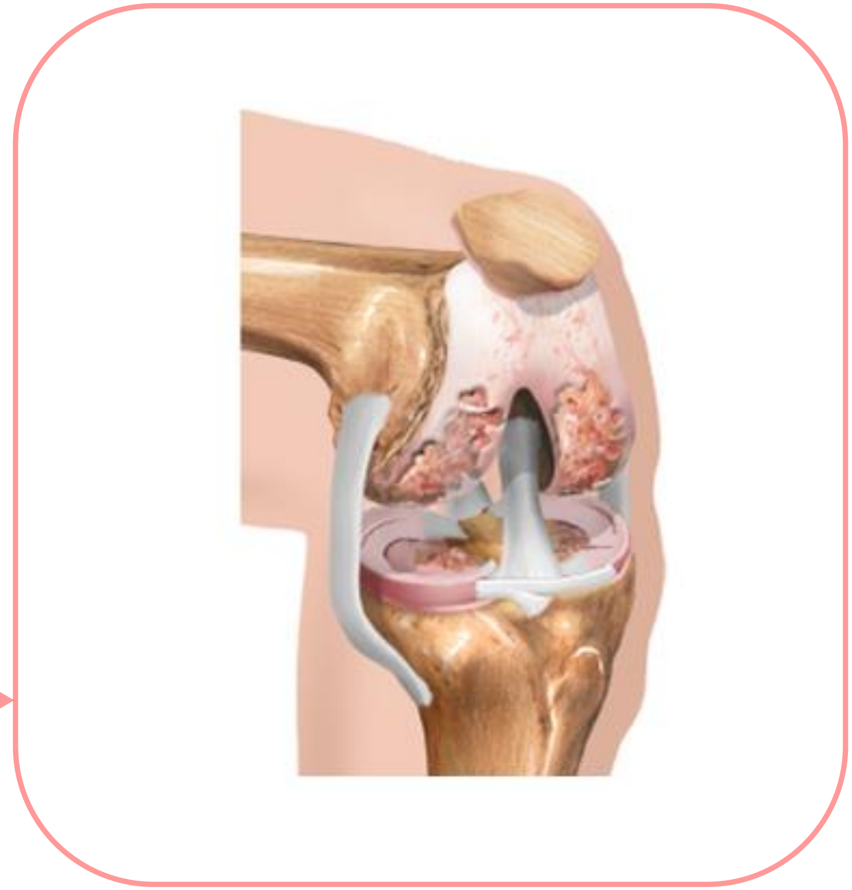
THE KNEE



THE KNEE



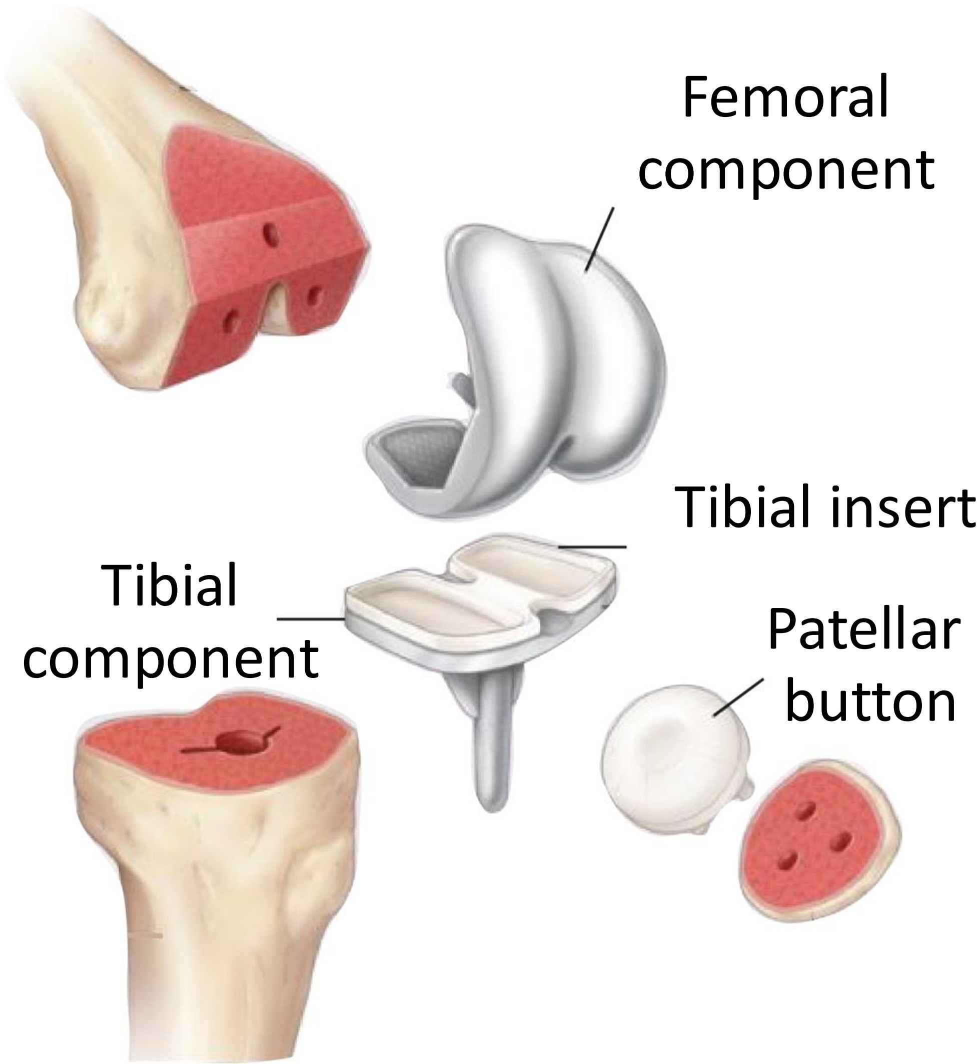
Osteoarthritis



> 30% of population over 65 years

[Barthel et al., 2009]

TOTAL KNEE ARTHROPLASTY



Up to 24% of revisions!

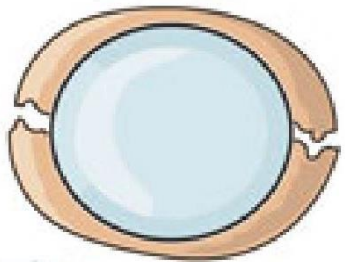
[Sundberg et al., 2014]

[Bozic et al., 2010]
[He et al., 2011]

- 1.1 million surgeries per year in USA & Europe
- satisfaction rate 70-86%, revision rate ~ 6%

PATELLAR COMPLICATIONS

Patellar fracture (up to 5.2%)[1]



Anterior knee pain
(at least 10%)[1]

?

Patient
Surgical technique
Implant design

↓

Bone strains[2,3]

↓

- Tissue damage
- Change in cell metabolic activity

↓

Fracture, Pain[4,5]

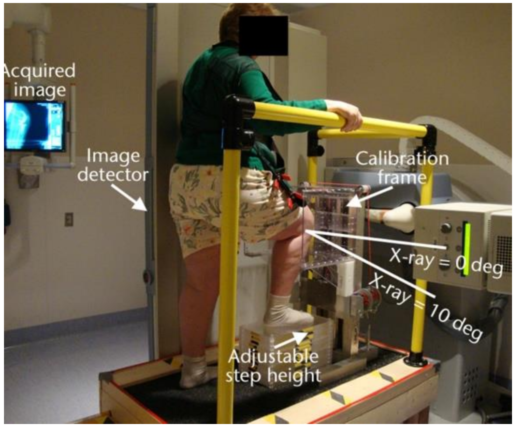
[1][Schindler, 2012] [3][Fitzpatrick et al., 2011]
[2][Lie et al., 2005] [4][Draper et al., 2011] [5][Ho et al., 2014]

PATELLAR STRAIN PREDICTION

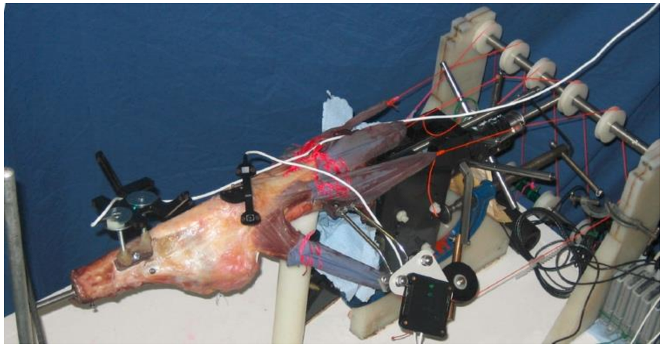
In vivo → Unavailable

In vitro → Limited
Not applicable to patient

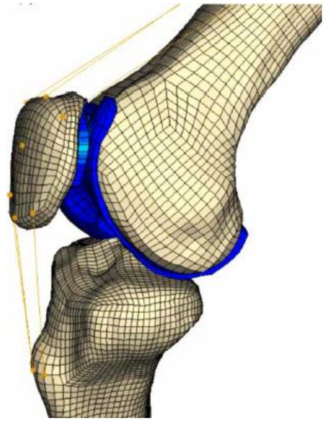
In silico → Numerical modeling



[Sharma et al., 2011]



[Merican et al., 2014]



[Fernandez et al., 2008]

Few studies[1]
Mainly cadaveric studies
Models not fully adapted to subjects
No validated material law for patella

[1][Fitzpatrick et al., 2011, 2013]
[Amirouche et al., 2013]
[Takahashi et al., 2012]

THESIS OBJECTIVES

Patient-specific knee model to evaluate patellar strain in TKA

1

Knee model

Kinematics, forces

2

Patellar model

Bone material properties

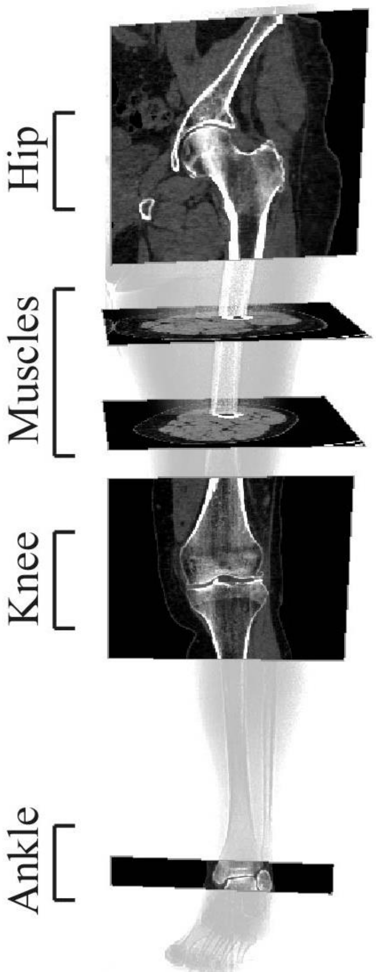
Strain

3

Application to the TKA patients

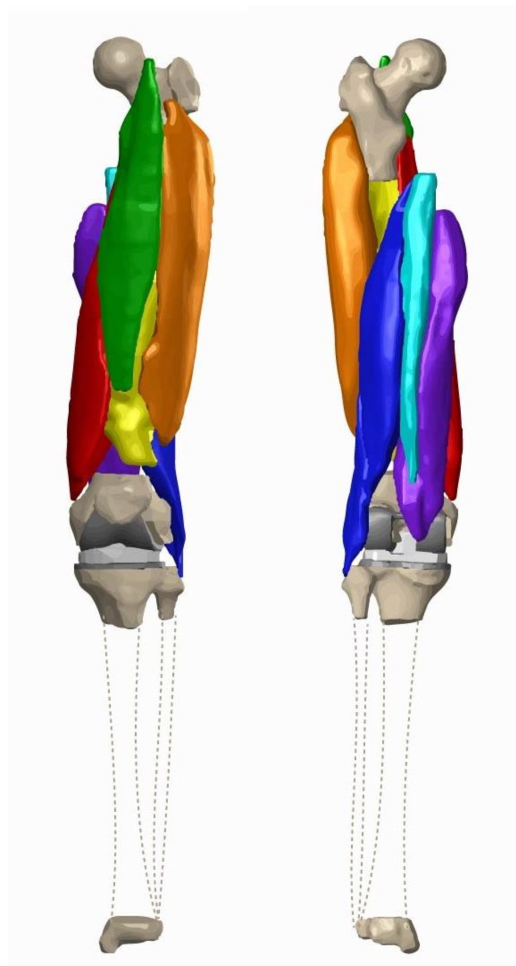
KNEE MODEL: GEOMETRY

Computer Tomography
(CT)



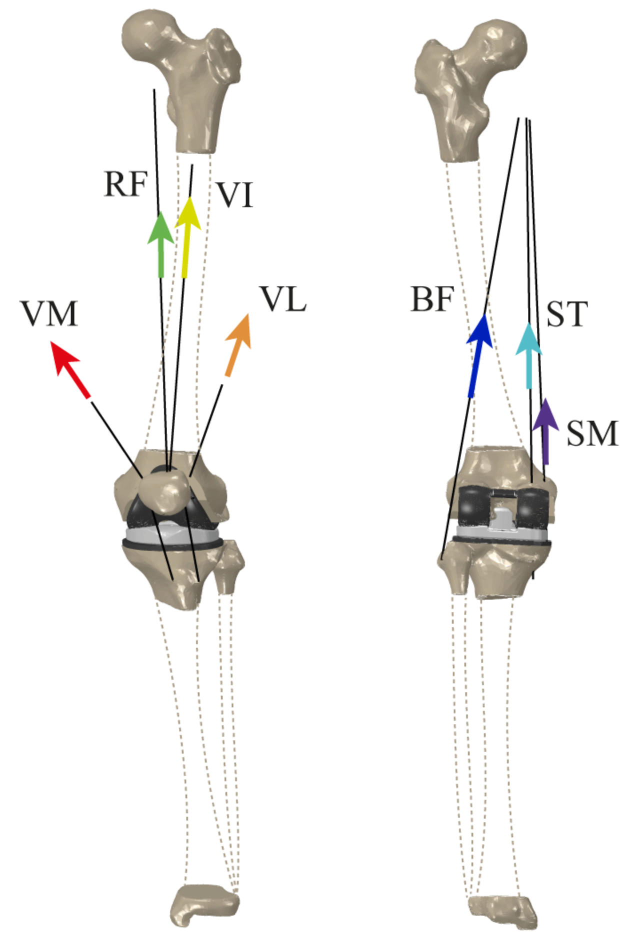
CHUV

Geometry reconstruction
Implant positioning

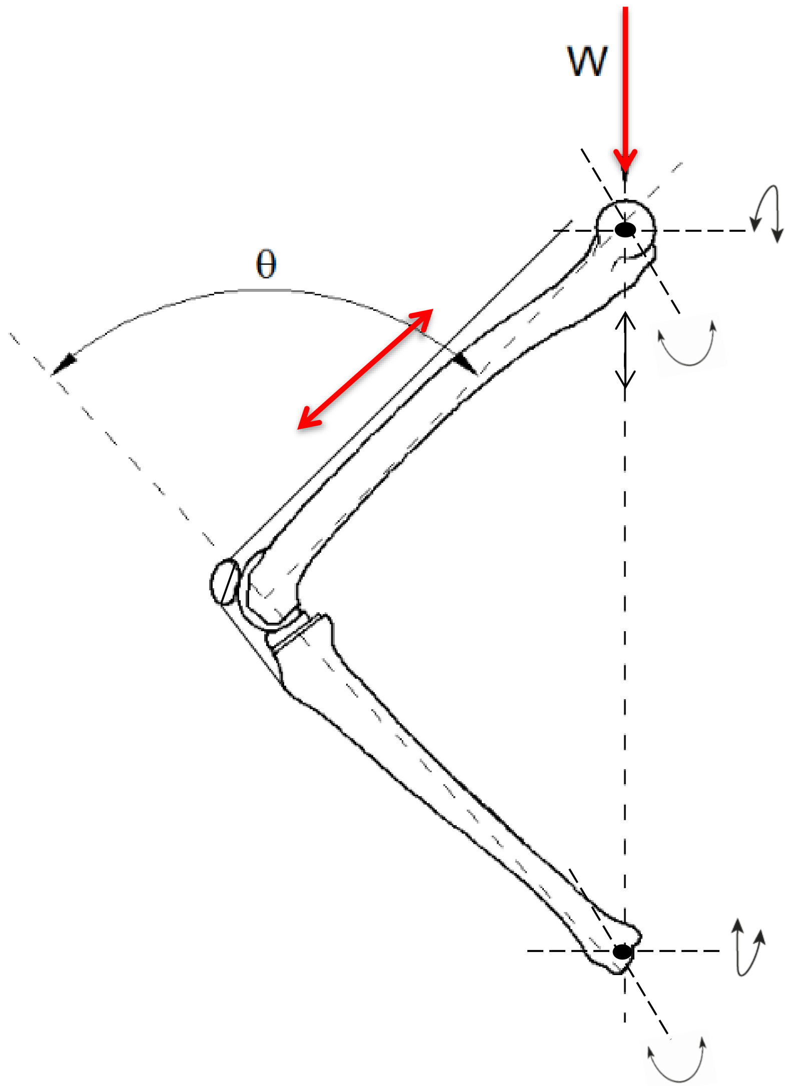


SYMBIOS

Numerical Model



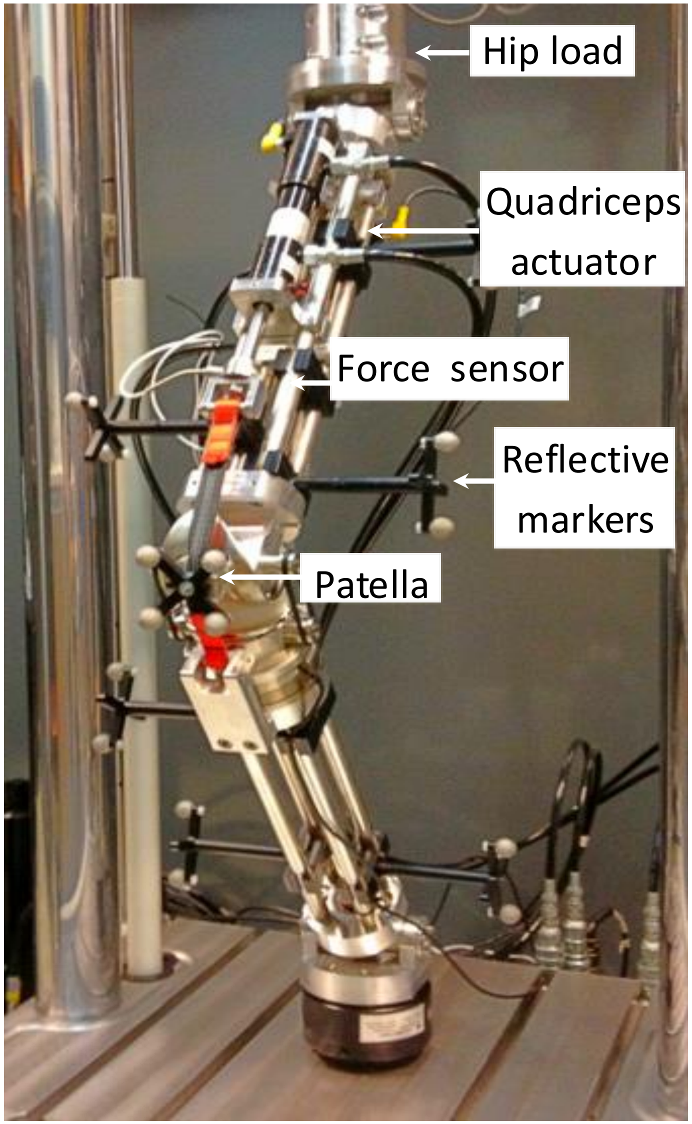
KNEE MODEL: BOUNDARY CONDITIONS



- Loaded squat (Oxford)
- Control: BW + muscle elongation + feedback algorithm[1]
- Force in muscles distributed according to muscle ratios (patient and literature)
- Abaqus/Standard

[1] [Terrier et al., 2007]

KNEE MODEL: VALIDATION



LMAM, EPFL

- Static squat: 10 to 60° (each 5°)
- Body load 300 N
- Self-learning algorithm[1]

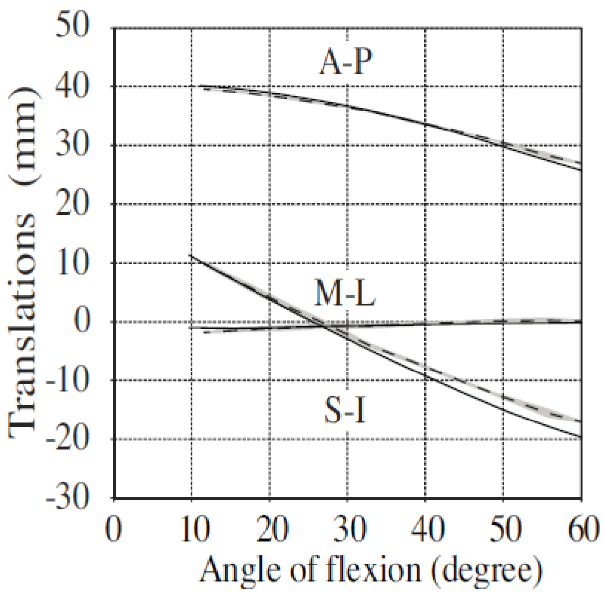
Measurements:

- Quadriceps force
- Patellar kinematics

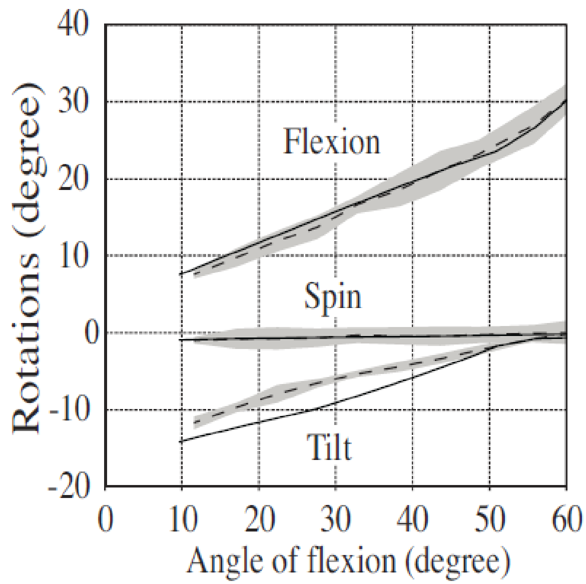
[1] [Arami et al.,2008]

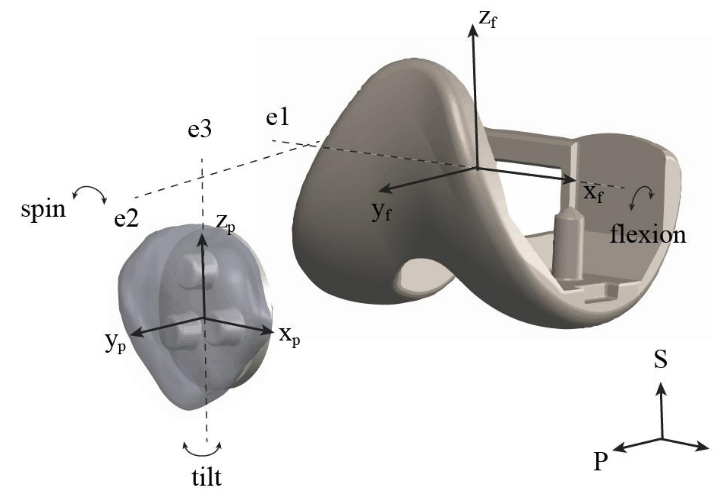
KNEE MODEL: VALIDATION (with experiment)

Average error: 0.6 mm



Average error: 1.1 degree

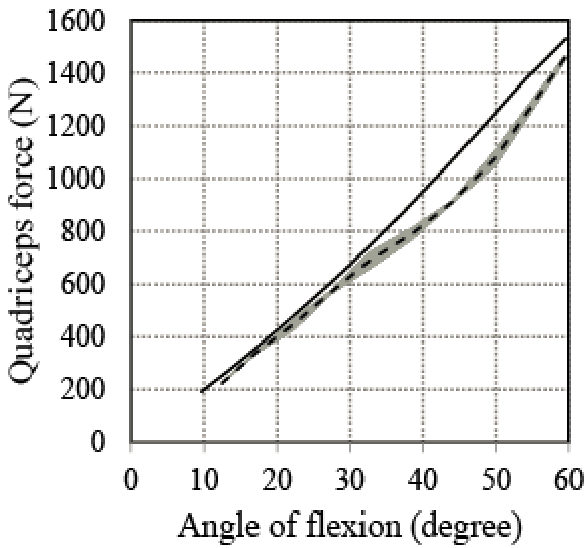




Three-cylinder open-chain system

[Grood and Suntay, 1983]

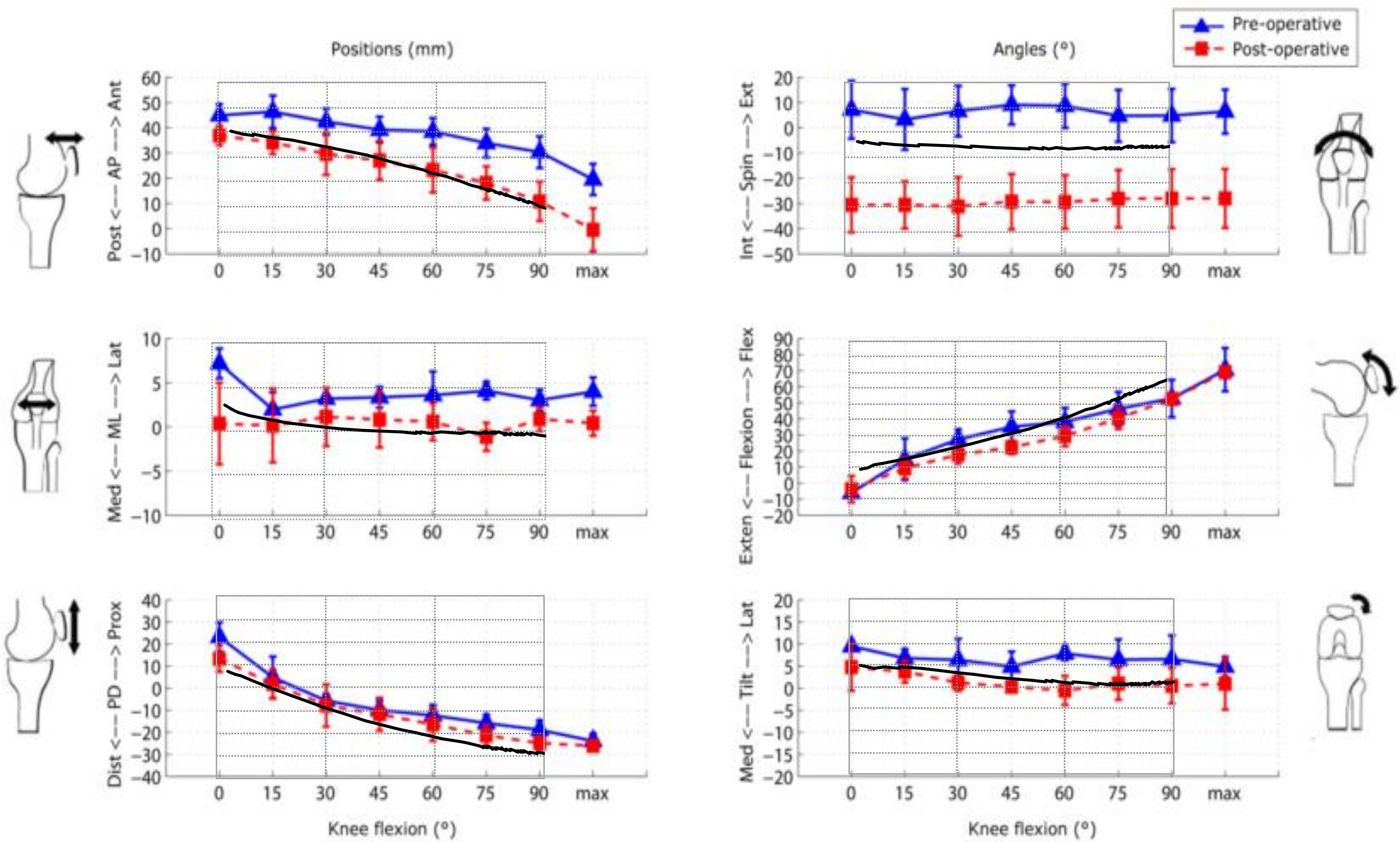
Average error:120 N



Experimental measurements

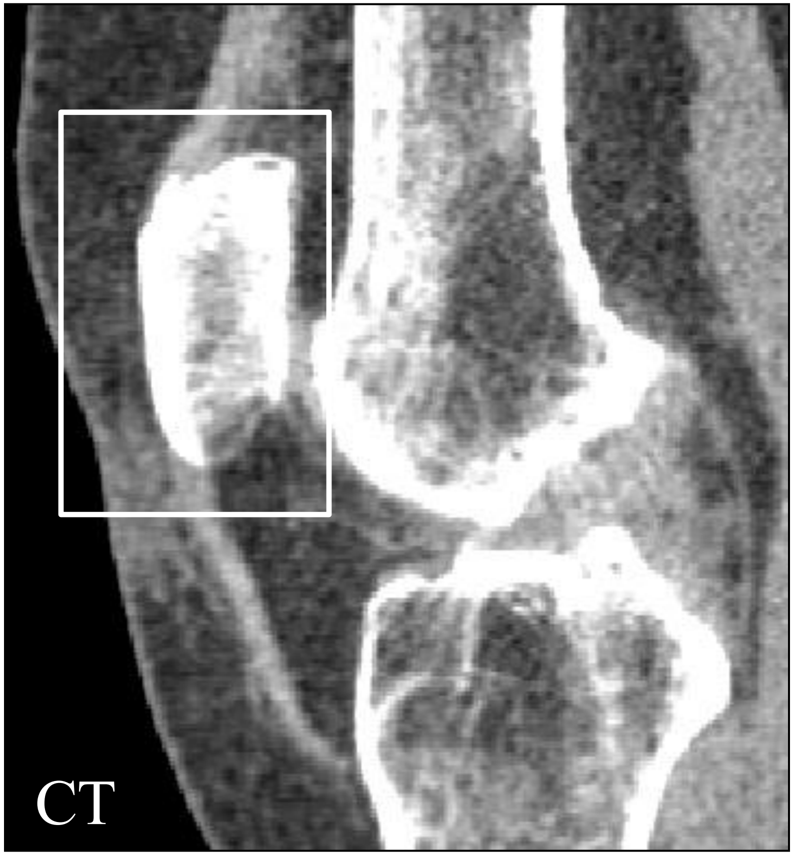
Numerical predictions

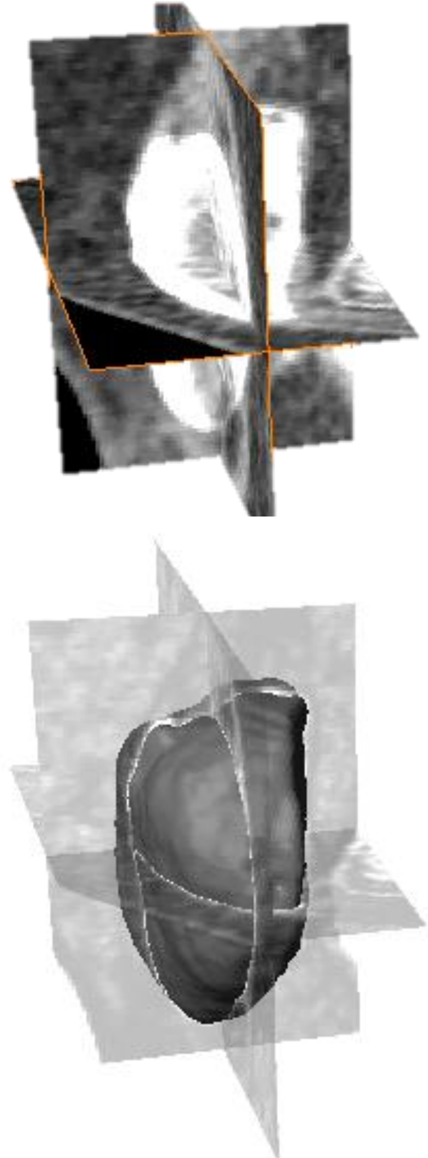
KNEE MODEL: VALIDATION (with literature)



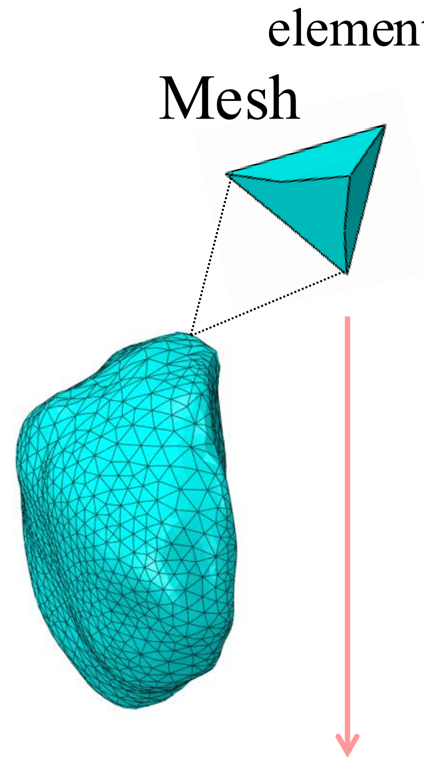
[Sharma et al., 2012]

PATELLAR MODEL





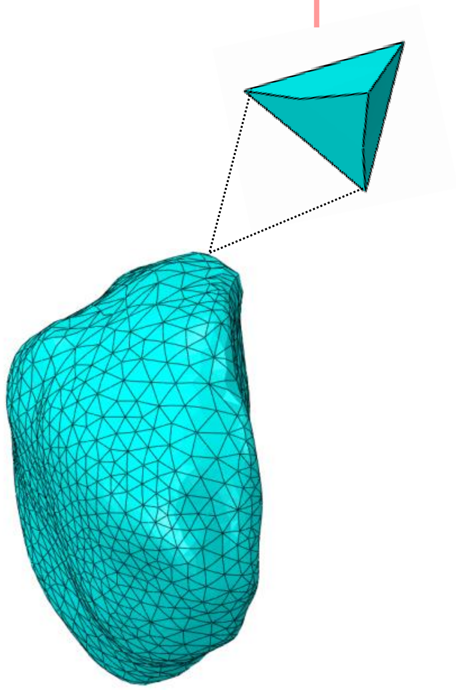
Geometry



Material properties

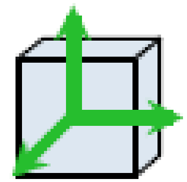
?

PATELLAR MODEL



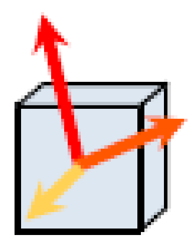
Homogenized
material properties

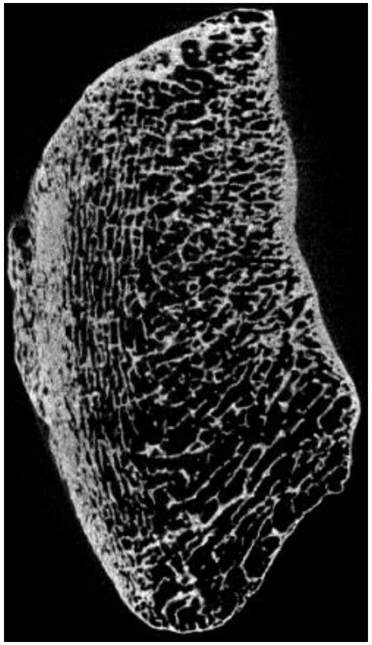
Isotropic



CT

Anisotropic
(orthotropic)

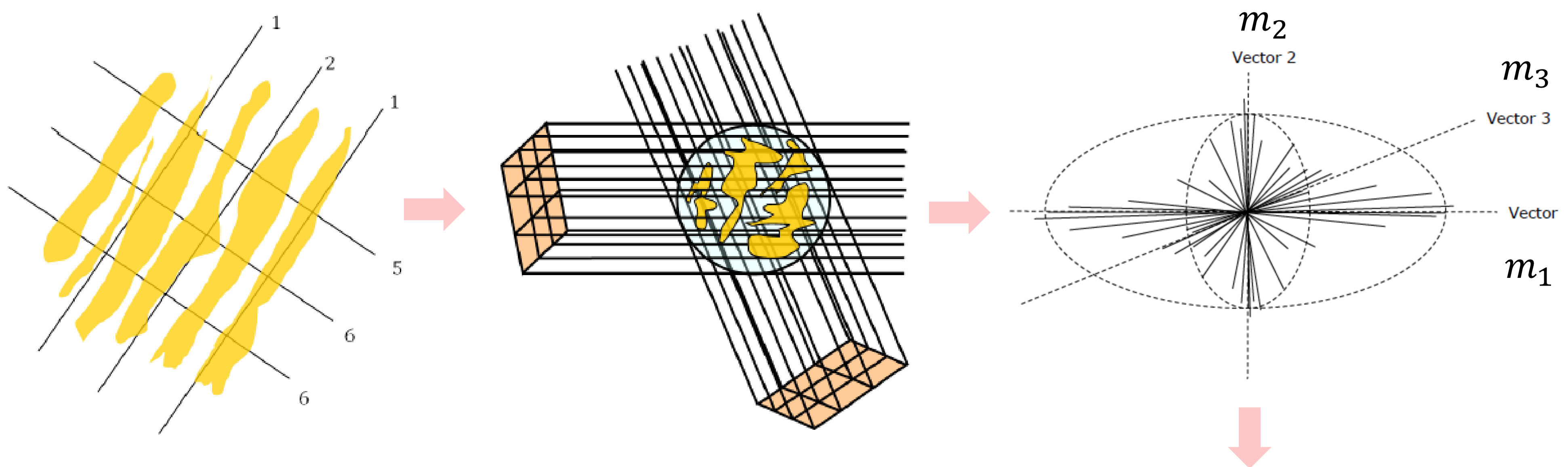




µCT

BONE ANISOTROPY

Mean intercept length (MIL) method → Fabric tensor



MIL is the mean distance between a change of phase (solid/liquid, (bone/marrow), with respect to a particular orientation

Fabric tensor

$$M = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$$

PATELLAR MODEL: MATERIAL LAW

Anisotropic linear elastic material $\varepsilon = C\,\sigma$

$$\boldsymbol{C} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & & & \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & & \mathbf{0} & \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & & & \\ & & & \frac{1}{2G_{23}} & & \\ & \mathbf{0} & & & \frac{1}{2G_{13}} & \\ & & & & & \frac{1}{2G_{12}} \end{bmatrix}$$

9 parameters → 5 constants + 4 variables

Morphology – elasticity relationship (Zysset – Curnier)[1]

$$E_i = E_0 \rho^k m_i^{2l}$$

$$\frac{E_i}{\nu_{ij}} = \frac{E_0}{\nu_0} \rho^k m_i^l m_j^l$$

$$G_{ij} = G_0 \rho^k m_i^l m_j^l$$

$$\forall\, i \neq j = 1,2,3$$

5 constants to identify: $\boldsymbol{E_0, \nu_0, G_0, k, l}$

4 (3+1) variables:
- M: fabric tensor[2]
- ρ: BV/TV (bone vol/total vol.)

<u>anisotropic model</u>

$m_1 \leq m_2 \leq m_3, tr(M) = 3$

<u>isotropic model</u>

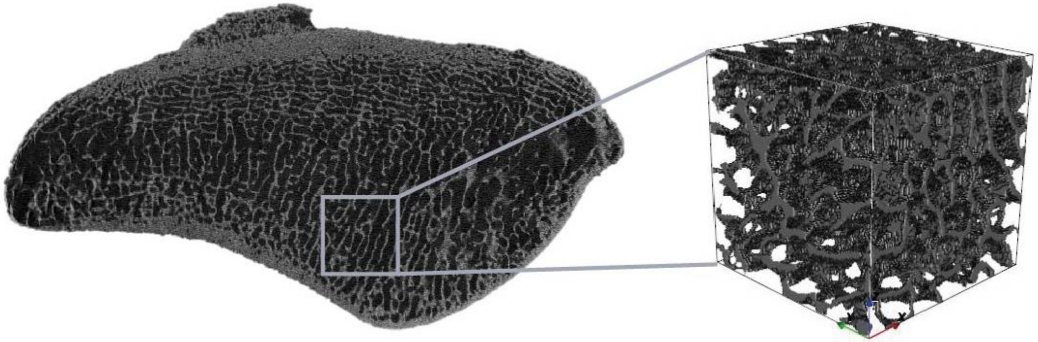
$m_1 = m_2 = m_3 = 1$

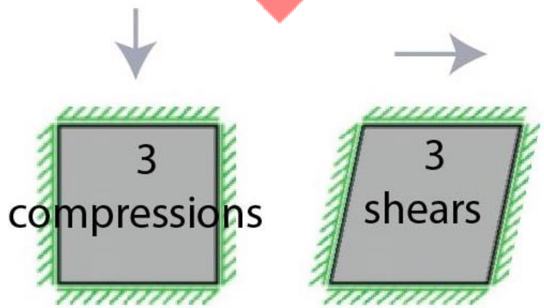
[1] [Zysset , Curnier, 1995]
[2] [Cowin, 1995]

IDENTIFICATION with μFE

μCT: 20 patellae

200 cubes (5.3 mm)





- Each voxel to hex element (E=12 GPa, v=0.3)[1]

[1][Wolfram, 2010, 2012]

- Kinematic Uniform BC[2]

[2][Pahr and Zysset, 2008]

- ≈ 9 million DOF

Stiffness

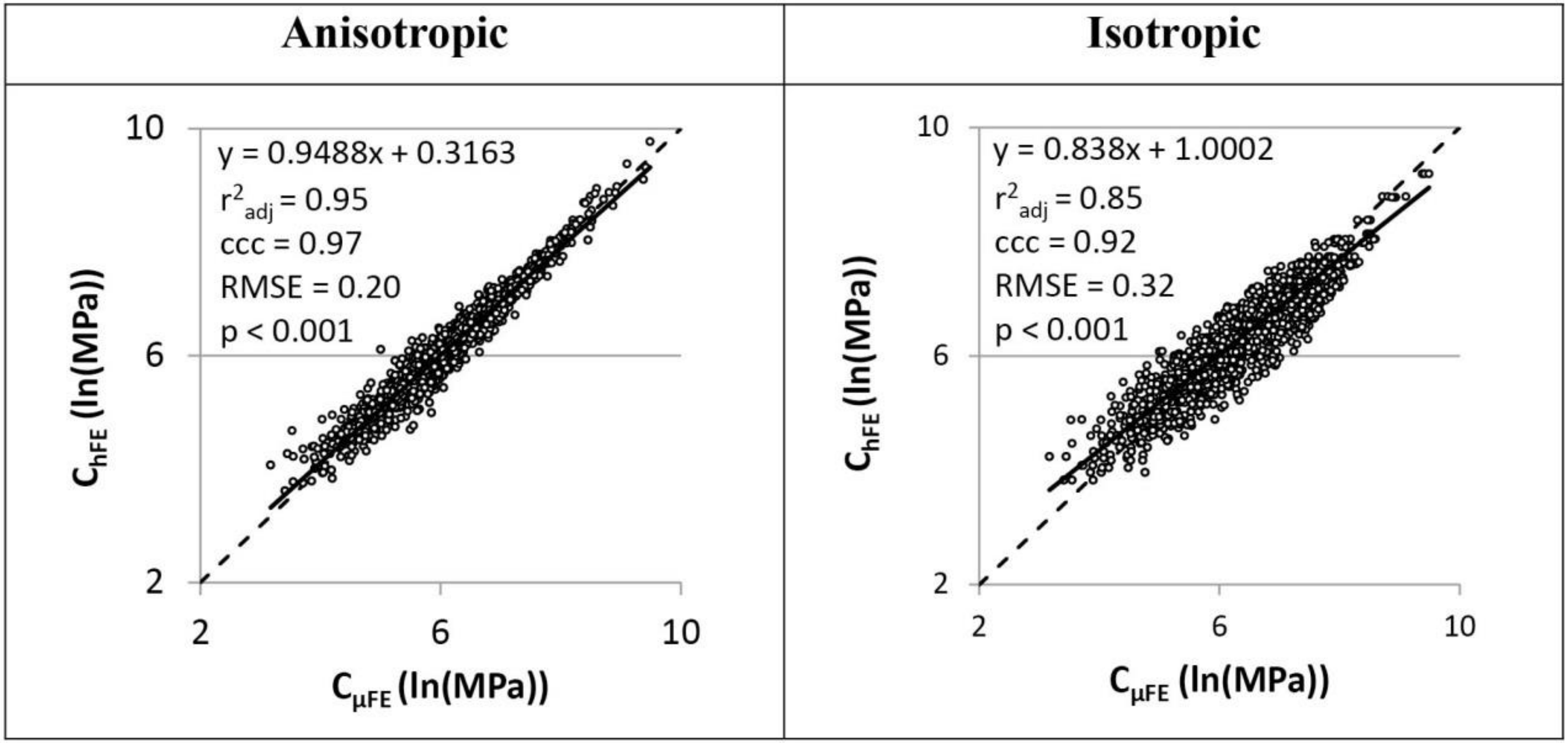
Fabric (MIL) + ρ

E_0, ν_0, G_0, k, l

anisotropic

isotropic

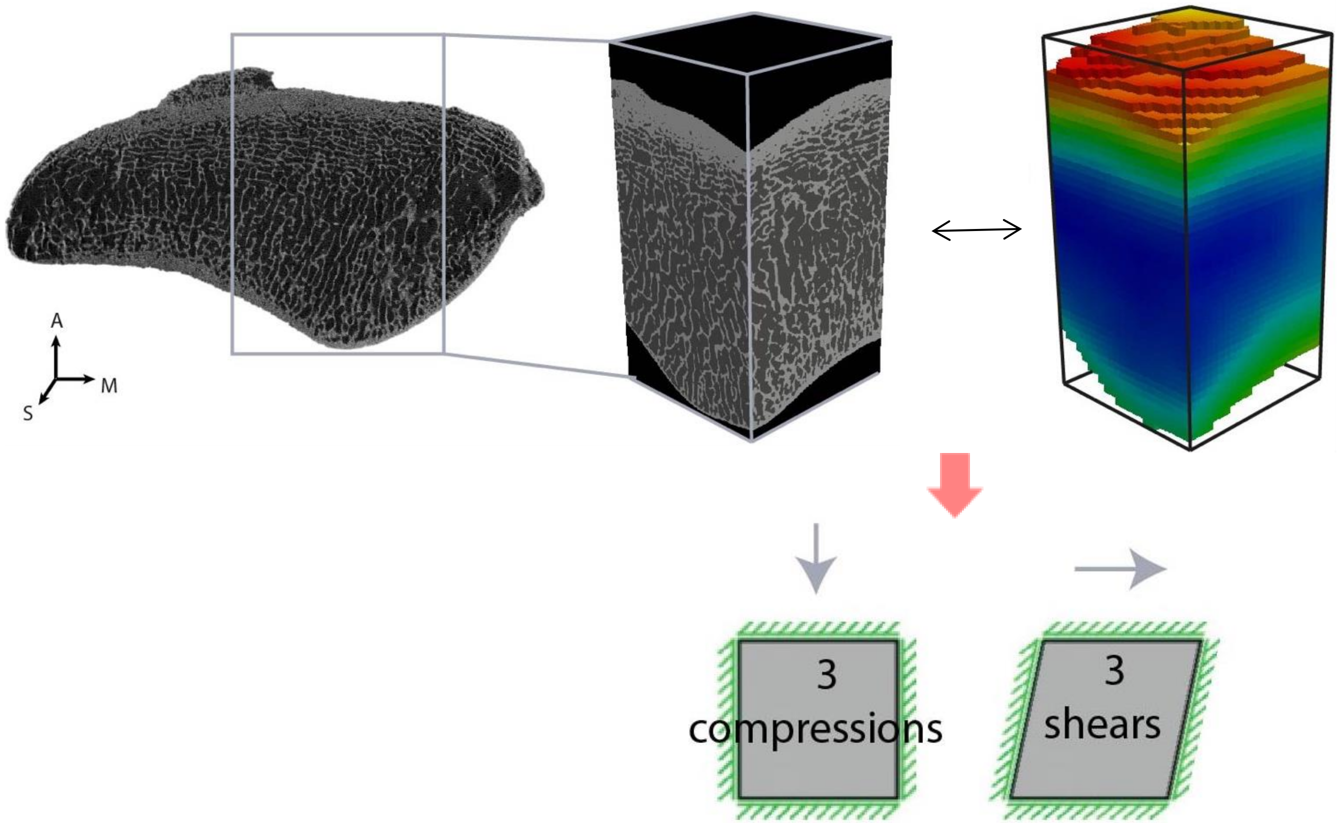
IDENTIFICATION with μFE

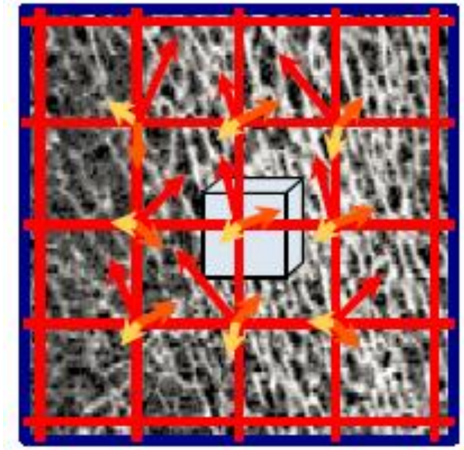


Law	E_0 (MPa)	ν_0	G_0 (MPa)	k	l
Anisotropic	12723.05	0.24	4224.62	2.1	1.02
Isotropic	11035.98	0.26	4395.05	2.13	-

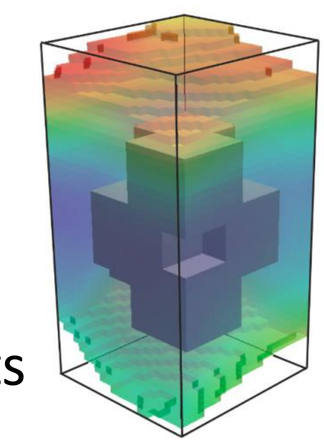
VALIDATION with μFE

μCT: 18 sections   μFE   hFE





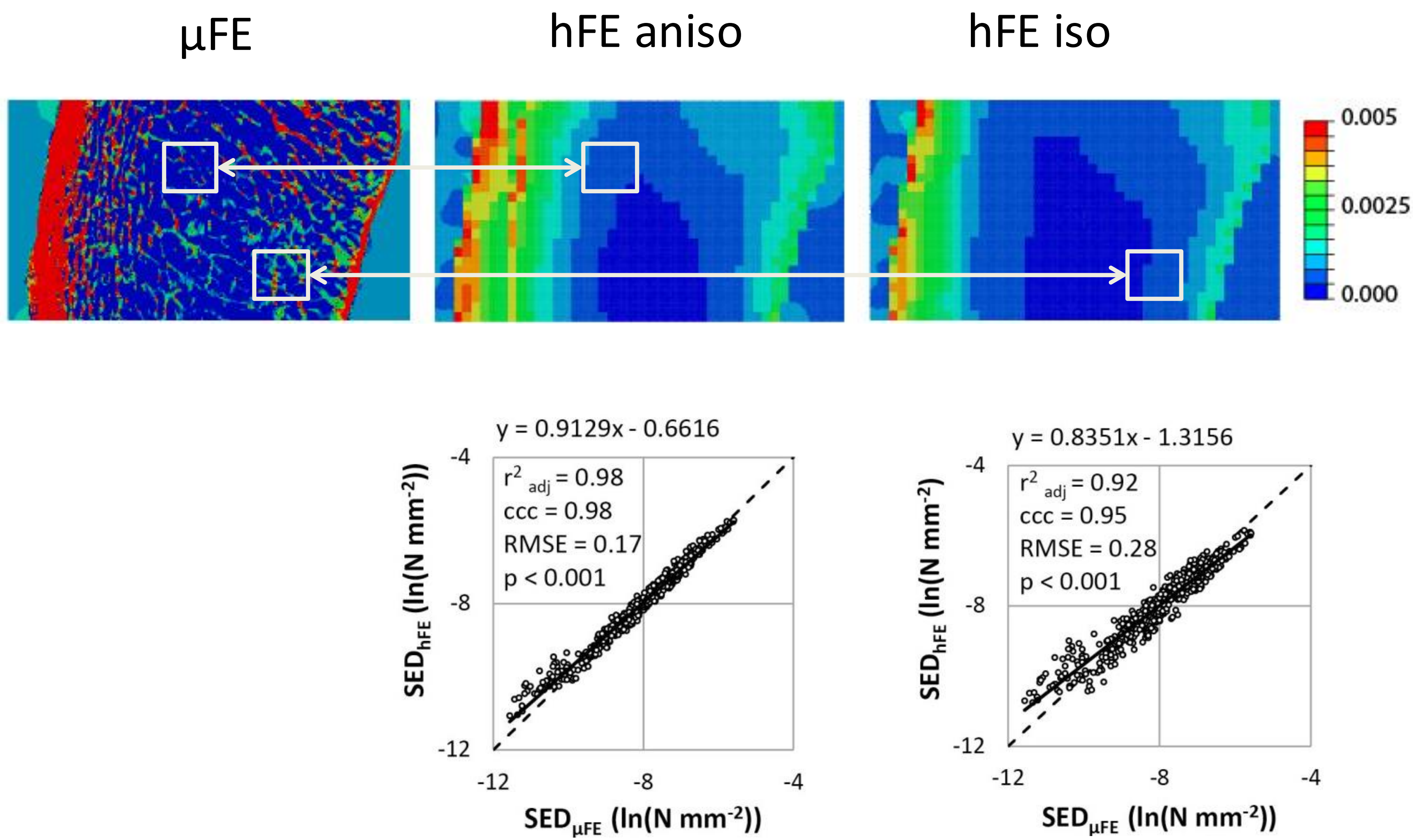
- hFE: anisotropic and isotropic
- Kinematic Uniform BC



Global comparison:
Stiffness

Local comparison:
Strain/stress invariants

VALIDATION with μFE



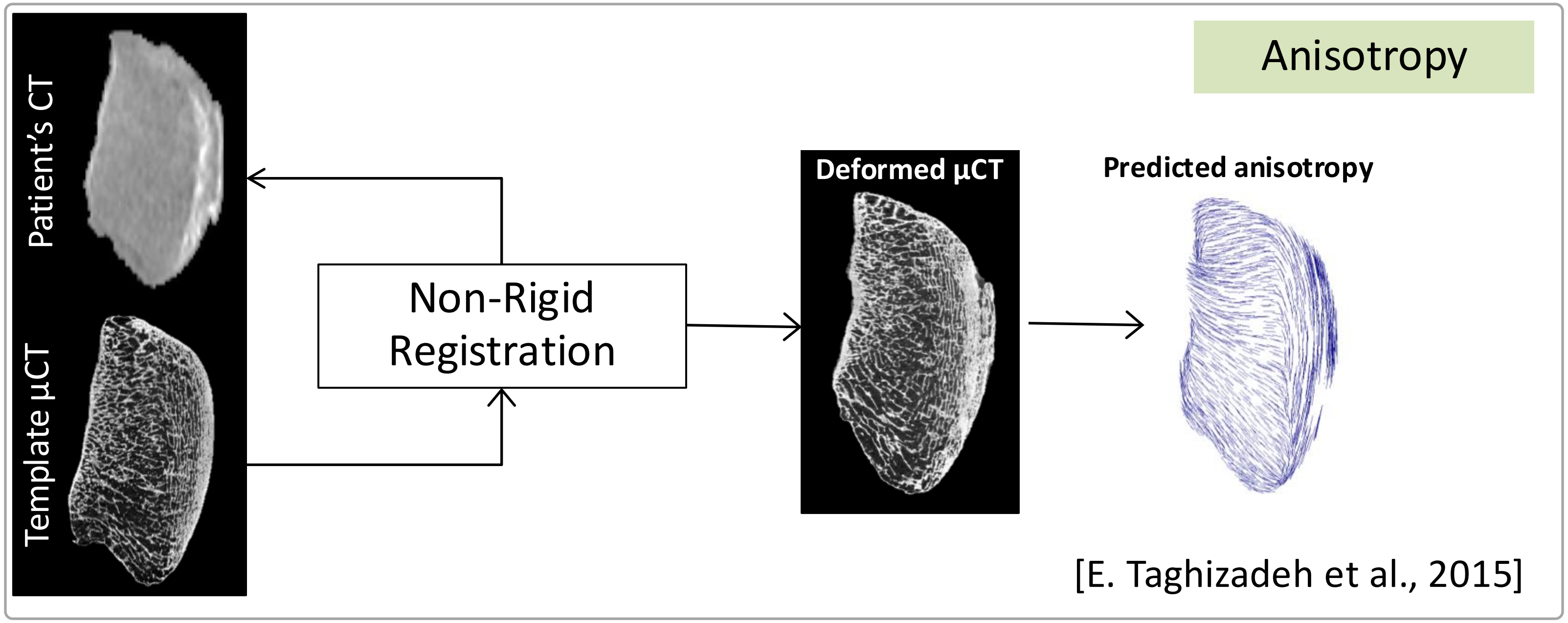
Strain energy density

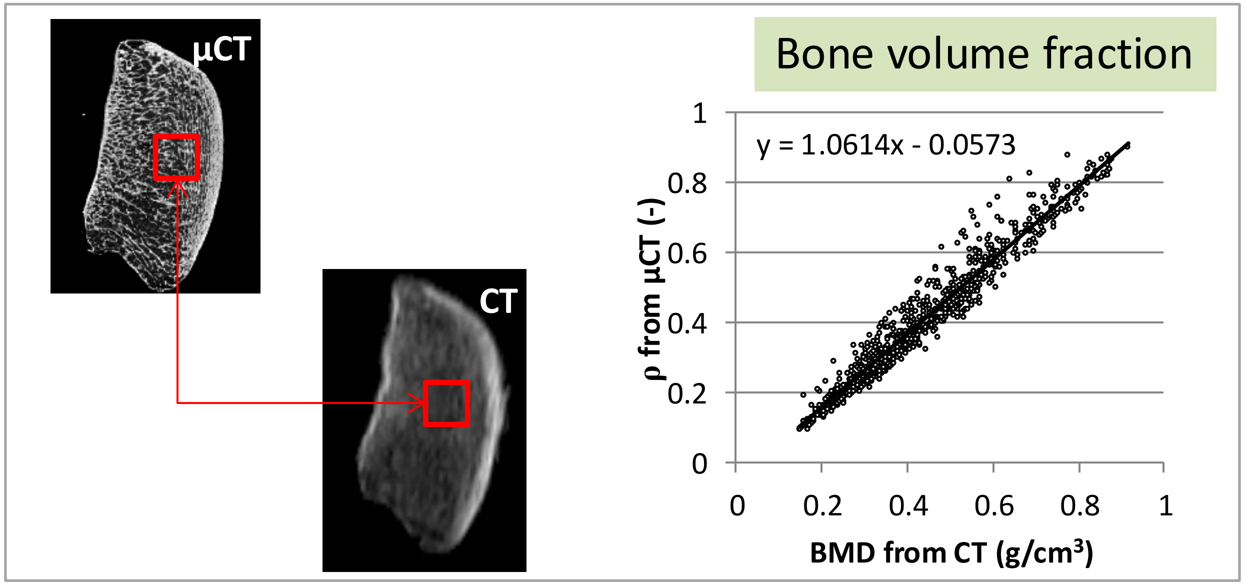
MATERIAL PROPERTIES FROM CT

Anisotropy?

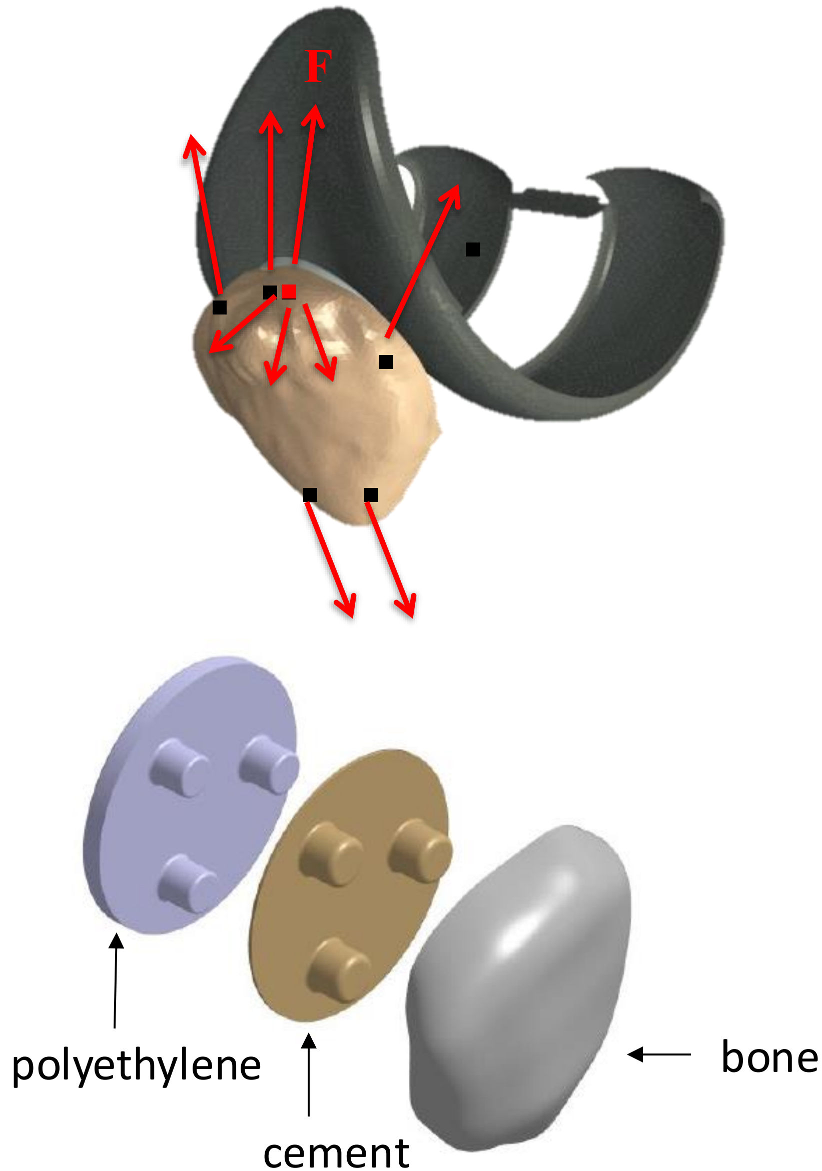
Bone volume fraction?

MATERIAL PROPERTIES FROM CT





PATELLA MODEL



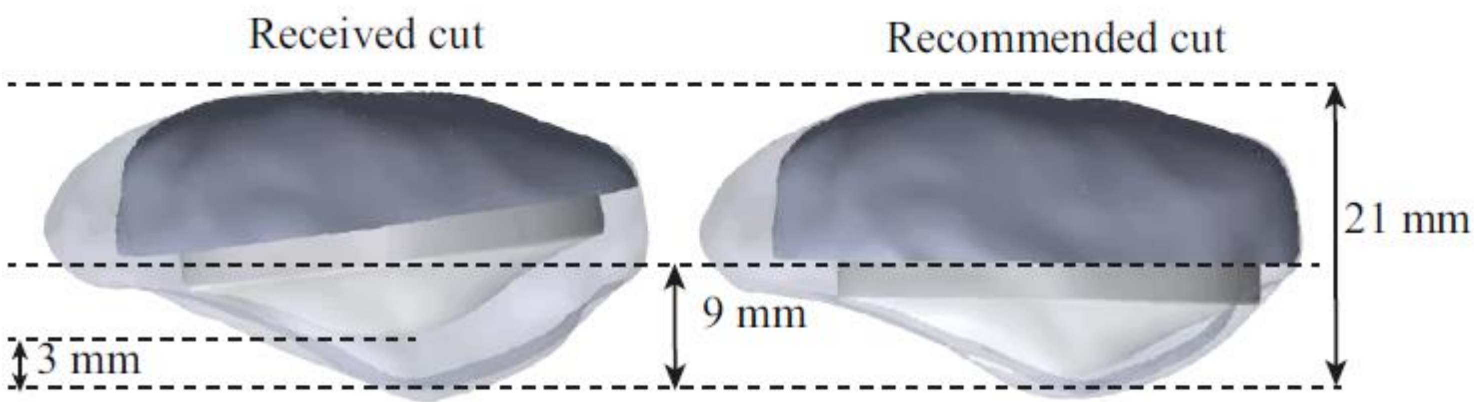
- Deformable patella (bone, cement, component) and femoral surface
- Translation and rotation according to knee model
- Forces along anterior bone surface with cubic weight function (Abaqus)

APPLICATION 1 : PATELLAR CUT

- 1 patient
- Preoperative CT & planning
- Patellar cut is more than recommended
- 8 months follow-up

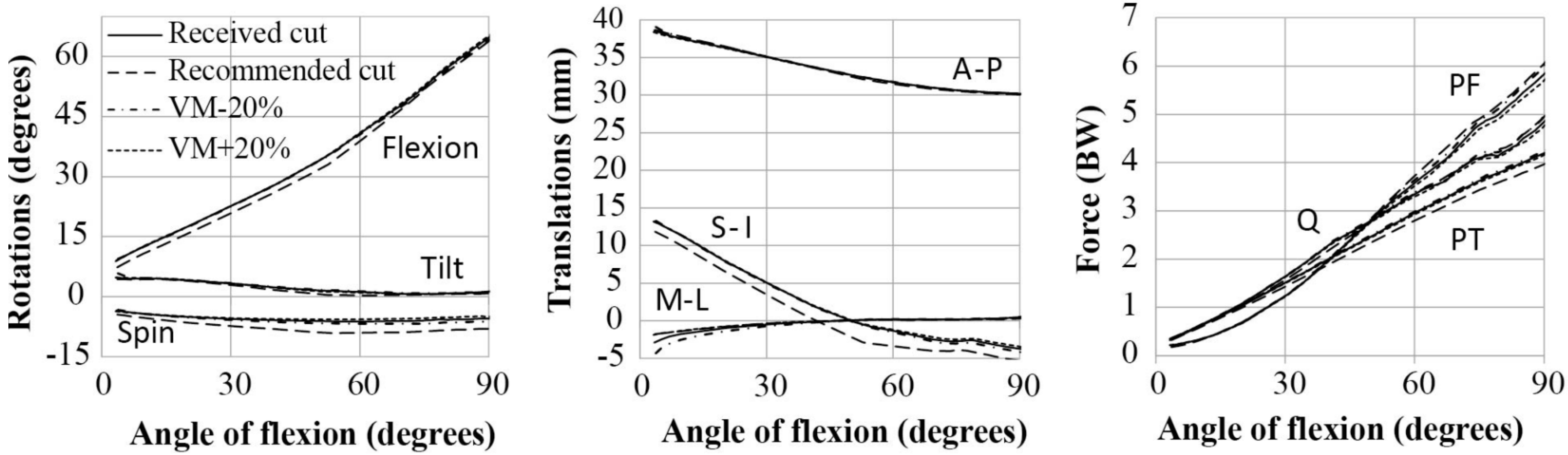
QUESTION:

- Does cut influence patellar mechanics?
- Does deeper cut increase risk of complications?
- Potential of the model?

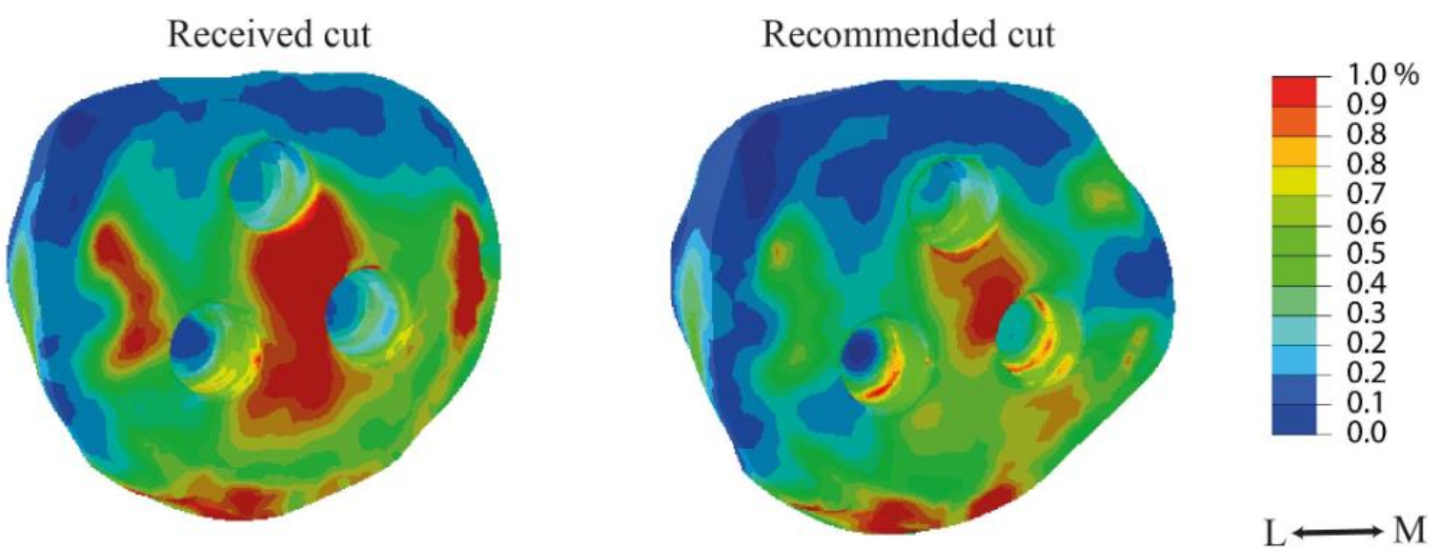


RESULTS

Kinematics and force



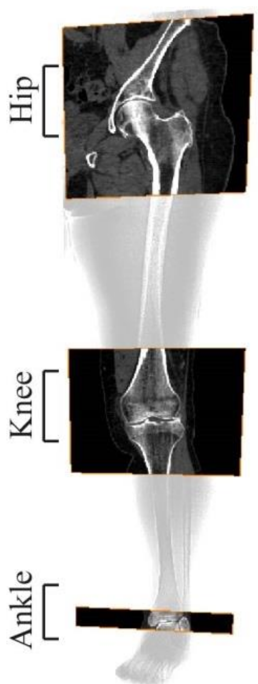
Strain



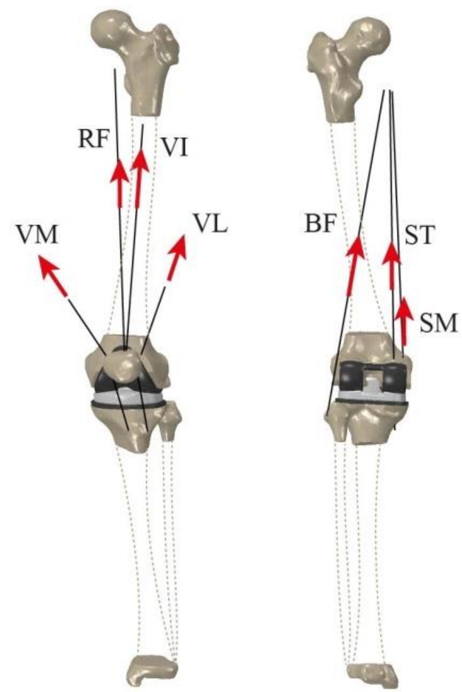
Deeper cut → higher strain!

APPLICATION 2: PATIENT-SPECIFIC STRAIN

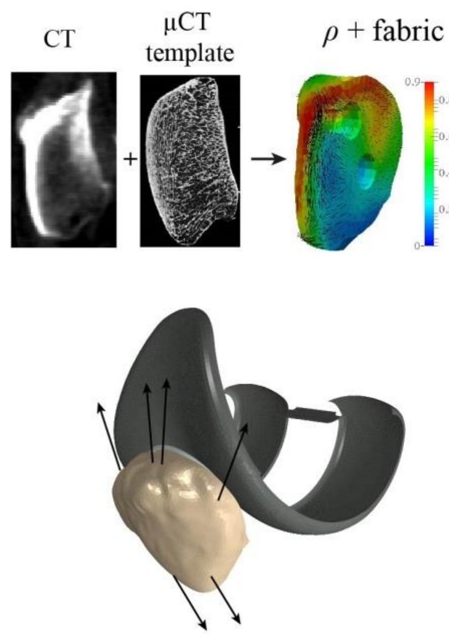
- 14 patients
- Preoperative CT & planning
- 1 year follow-up
- No complications
- Patellar cut from post-op X-Ray
- Loaded squat (BW)
- Muscles ratios (literature)
- Octahedral shear strain at 60° of knee flexion



Patient



Knee model

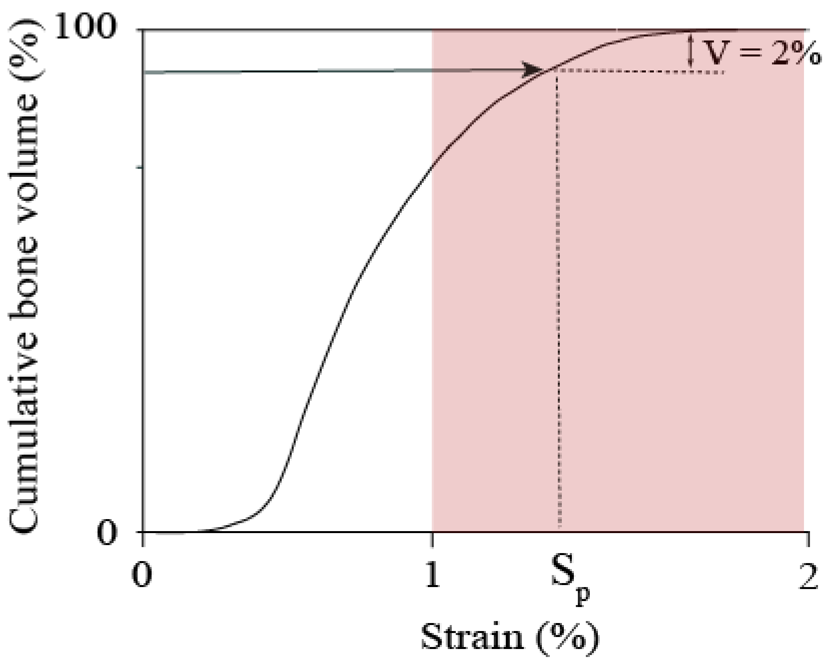


Patella model

QUESTION

- Variation between patients
- Correlation between strain and patient parameters:
    - Age
    - Sex
    - Height, weight, body mass index (BMI)
    - Patellar volume after resurfacing (V)
    - Bone mineral density (BMD)
    - Combination of parameters

APPLICATION 2: DAMAGE CRITERION



Bone damage :

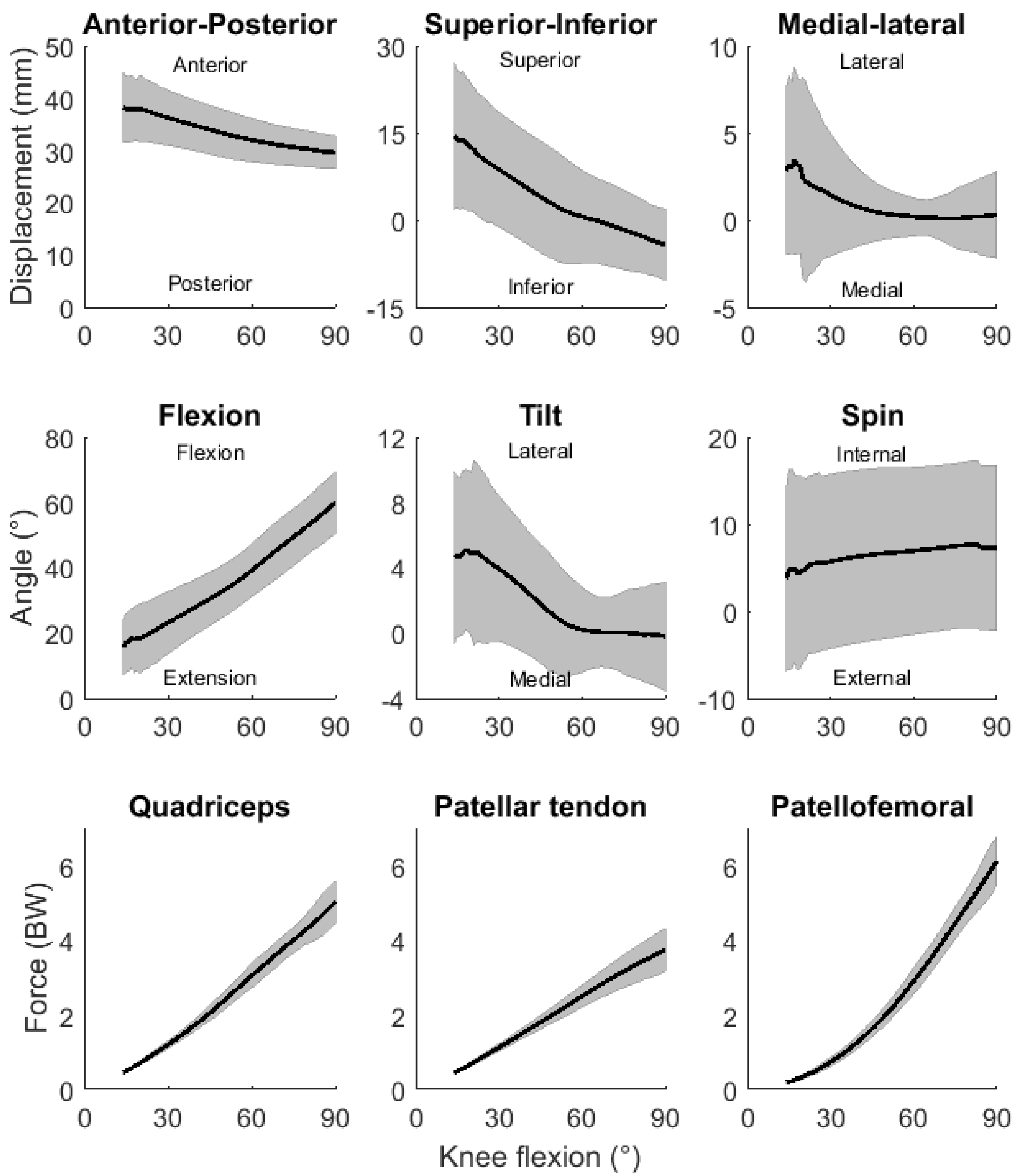
- 2% of bone volume above bone yield
- Bone yield ~ 1-2% of strain

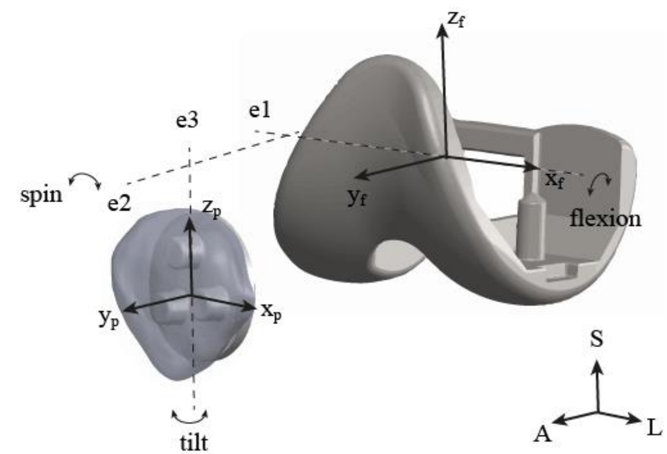
[Pistoia et al, 2002]

Strategy :

- Estimate S_p for each patient
- Sp > bone yield → patient under risk

RESULTS: KINEMATICS AND FORCES

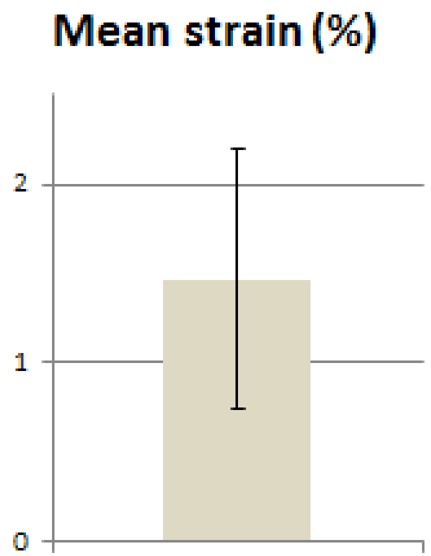


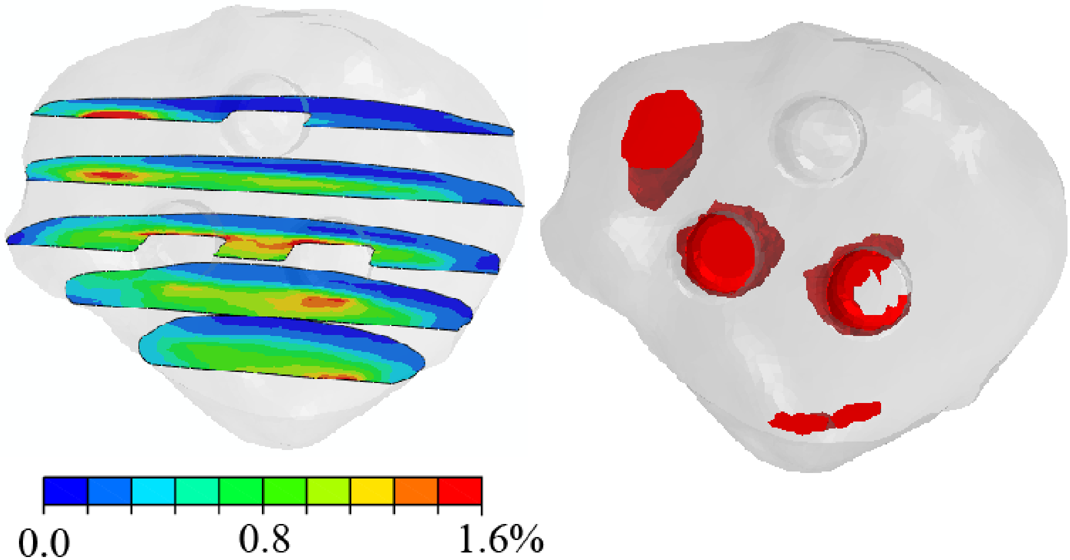


RESULTS: PATELLAR STRAIN

- Example for patient #5

M ⟷ L

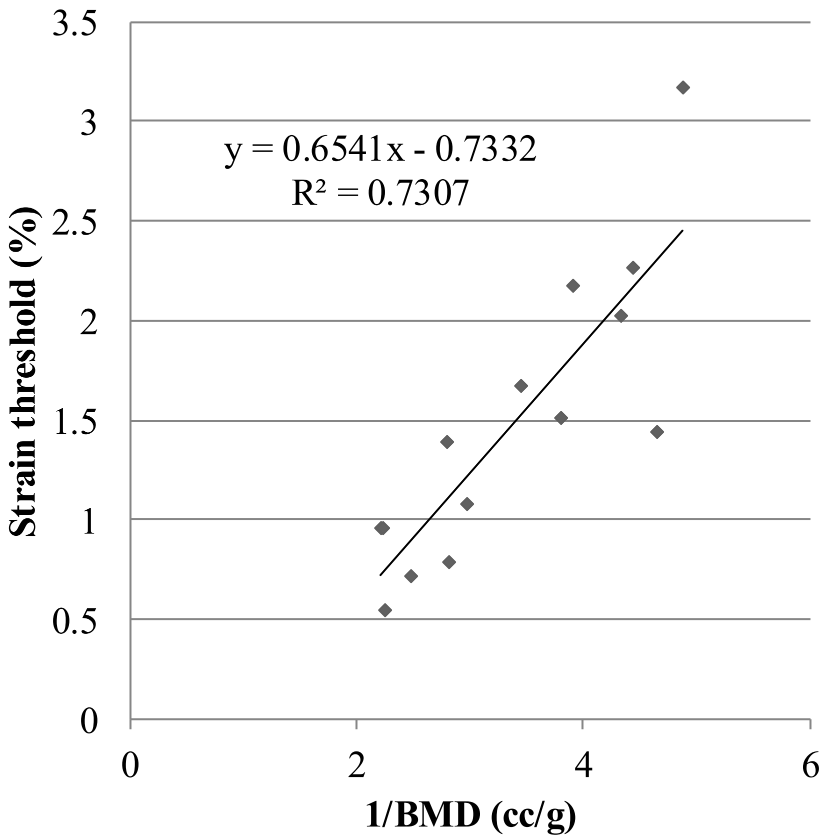


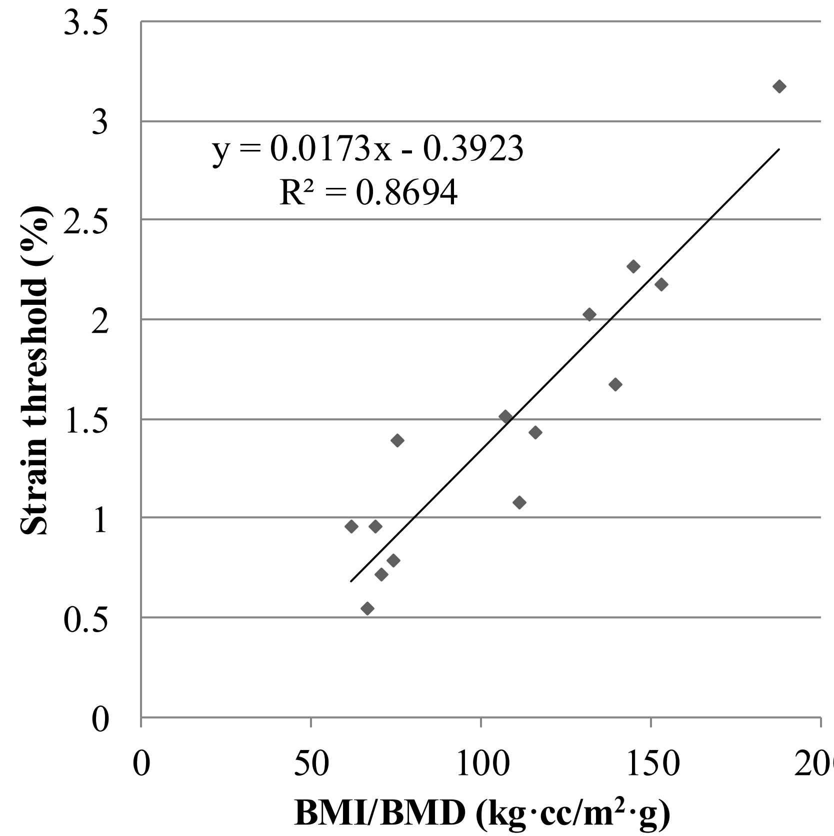


Strain distribution

2% of highly strained bone

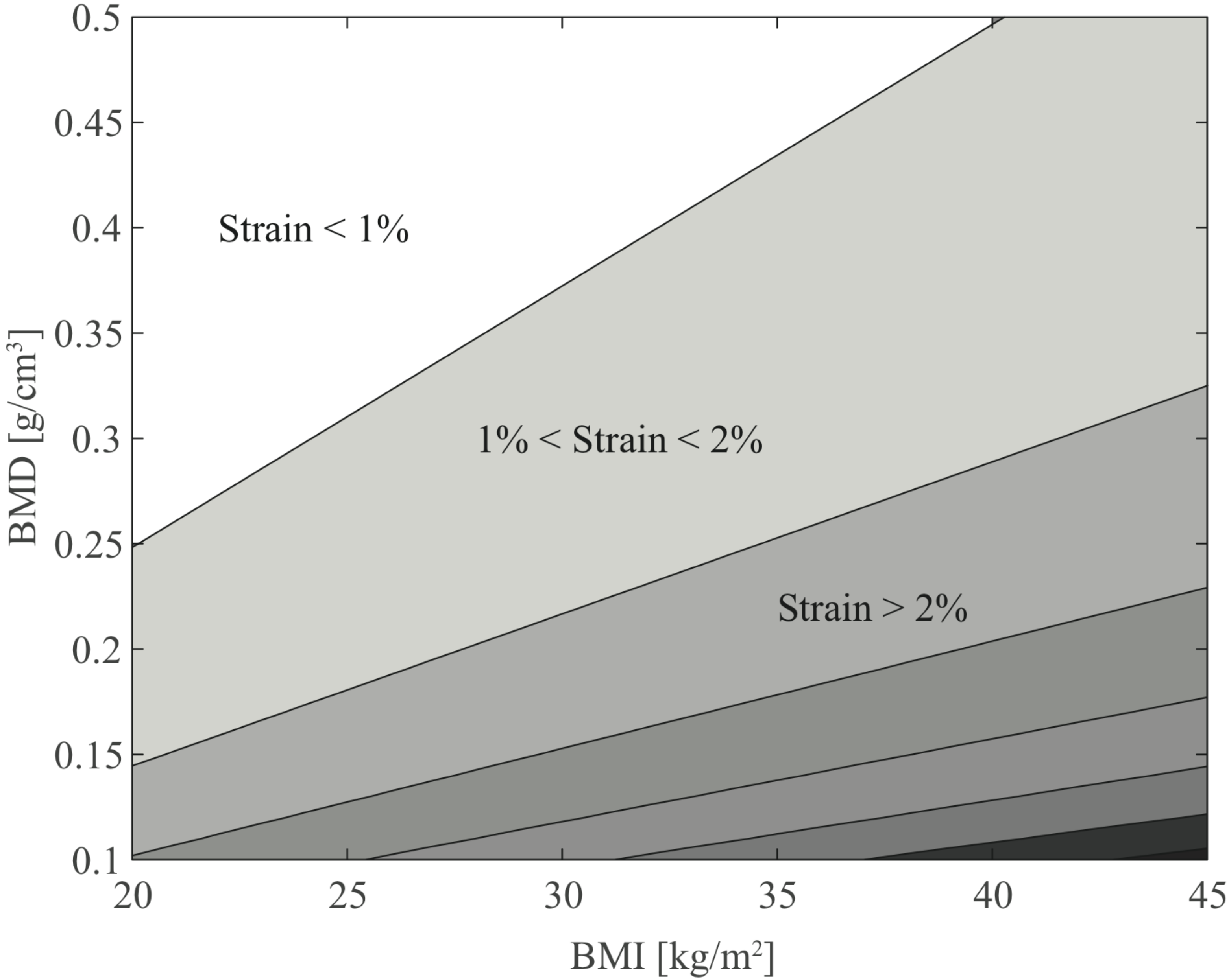
RESULTS: CORRELATIONS





BMD - Bone Mineral Density
BMI - Body Mass Index

RESULTS: RISK PREDICTION



Latypova et al., Medical Engineering & Physics, 2019, 68:17-24

CONCLUSIONS

- Developed patient-specific TKA model with focus on patella
- Originality:
  - Muscle control
  - Adaptation to anatomy, implant design, and position, body weight
  - Identified and validated patellar material properties (anisotropic and isotropic)
- Application to patients:
  - Highlighted the importance of the patellar cut
  - Highlighted the importance of the patellar density and BMI in preoperative planning
  - Potential of the model as a surgery planning tool

NEXT STEP: CLINICAL APPLICATION

- Clinical retrospective study
- 2 groups of patients, with >2 years follow-up
  - Patients with patellar complications after TKA
  - Patients without complications after TKA
- Radiological evaluation of preoperative patellar BMD
- Statistical differences of BMD & BMI
- Clinical recommendation